

Numerical Investigation of Nonlinear Internal Wave Generation and Breaking in Straits

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LONG-TERM GOALS

Our long-term goals are to develop a physical understanding of the processes which lead to mixing in the ocean, with the aim of using this understanding to develop parameterizations of mixing suitable for global and regional models, and applying such models to societally relevant problems. A particular focus is the mixing induced by tidal flow over topography, and mixing induced by breaking nonlinear internal waves.

OBJECTIVES

The scientific objectives of this study are to explore internal waves generated by tidal flow through straits in the region close to the sill. Our geographic focus is the Luzon Straits. A particular scientific focus is nonlinear overturning and breaking within the straits leading to mixing and modification of the wave field. One possibility which we examine is whether transient internal hydraulic jumps are possible in the Luzon Straits, whether these jumps are released to propagate toward the topography as internal bores when the flow relaxes, and whether the bores lead to local mixing. We explore the details of the Luzon Strait topography to identify locations particularly conducive to local overturning processes. The Luzon Strait features two parallel north south oriented ridges; we examine how the wave fields of the two ridges interact and affect wave generation and mixing processes. We also examine the importance of three-dimensional bathymetry in determining the locations of mixing. To summarize, our goals are to (a) examine the dependence of nonlinear features and local breaking at the generation site on topographic shape and stratification; (b) evaluate how the interaction between the ridges affect the mixing; (c) examine the extent to which the mixing processes are determined by three-dimensional topography variations.

APPROACH

We employ the nonhydrostatic MITgcm in both 2- and 3-dimensions to carry out simulations of increasing complexity, focusing the resolution on the regions close to the sill where overturning is most likely to occur. The MITgcm is well-suited for this study, having been used for numerous studies of nonlinear internal tides (e.g. Legg and Klymak, 2008). MITgcm is a z -coordinate model and it applies a simple vertical dissipation and mixing scheme that computes vertical viscosities and

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diffusivities computed by Thorpe sorting unstable density profiles (Klymak and Legg, 2010). Typical resolutions near the sill are $O(100\text{m})$ in the horizontal and $O(10\text{m})$ in the vertical. Most calculations have been performed on the NAVY cluster Da Vinci.

High resolution 2D simulations were carried out in 2010-2011 to investigate the double ridge internal wave interference and its effect on turbulent mixing. These results have been published in the Journal of Physical Oceanography (Buijsman et al, 2012).

Small-scale 3D simulations have focused on providing guidance for the main field program which took place in summer 2011, aiding observationalists Rob Pinkel and Jody Klymak in finding dissipation hotspots on top of the East Ridge in Luzon Strait (Pinkel et al, 2012). Following the field program, in the past year regional low and high resolution 3D simulations have been carried out to help in the interpretation of the observations, and to study the influence of the 3D topography on the dissipation and double ridge internal wave interference. Most of the work is being carried out by Maarten Buijsman, a postdoctoral researcher based at Princeton, and we are collaborating closely with Jody Klymak. We are also communicating closely with other observationalists involved in the Luzon Straits field experiment.

WORK COMPLETED

Funding was awarded in spring of 2009, but Maarten Buijsman only joined the project in September 2010. The project is near its end after two years. In the first year we completed a 2D study of the impact of topographic shape on the nonlinear waves, breaking and dissipation in the straits, comparing results with observations from the 2010 Luzon Straits pilot study. 3D calculations for the purposes of guiding the observations in 2011 summer were also carried out. In the second year, the first year's work has been documented and published (Buijsman et al 2012, Klymak et al 2012a, Klymak et al 2012b, Pinkel et al 2012), and regional low and high resolution 3D model runs have been performed to examine the effect of 3D topography on the nonlinear waves and dissipation. These 3D results are discussed below in more detail.

RESULTS

Three-Dimensional Internal Wave Double Ridge Interference

Although the double ridge internal tide interference is fairly well understood in the 2D sense, it is not yet clear how this plays out in three dimensions. Following the 2D model experiments by Buijsman et al (2012), we apply the MITgcm to three ridge configurations: a double ridge, a single west ridge, and a single east ridge, and to semidiurnal and diurnal internal tides. The model features a stretched grid with a high horizontal resolution of 2 km in the central region that covers the entire Luzon Strait, and 50 vertical layers that feature a higher resolution near the surface and a lower resolution near the bottom. The stratification, obtained from Alford et al (2011), is horizontally uniform. The three configurations are run for 6 days when semidiurnal tides are dominant and when diurnal tides are dominant. These two periods coincide with measurements conducted in the summer of 2010 (Alford et al, 2011). The 3D model predicts the barotropic velocities at the west ridge at stations N2a and N2b better than the 2D model (Figure 1). This is attributed to the steering and blocking of the barotropic flow by the ridges, absent in the 2D model, causing stronger velocities at the west ridge than in the 2D model. Moreover, the timing and amplitude of the baroclinic velocities and isotherm oscillations of the data and 3D model are in reasonable agreement.

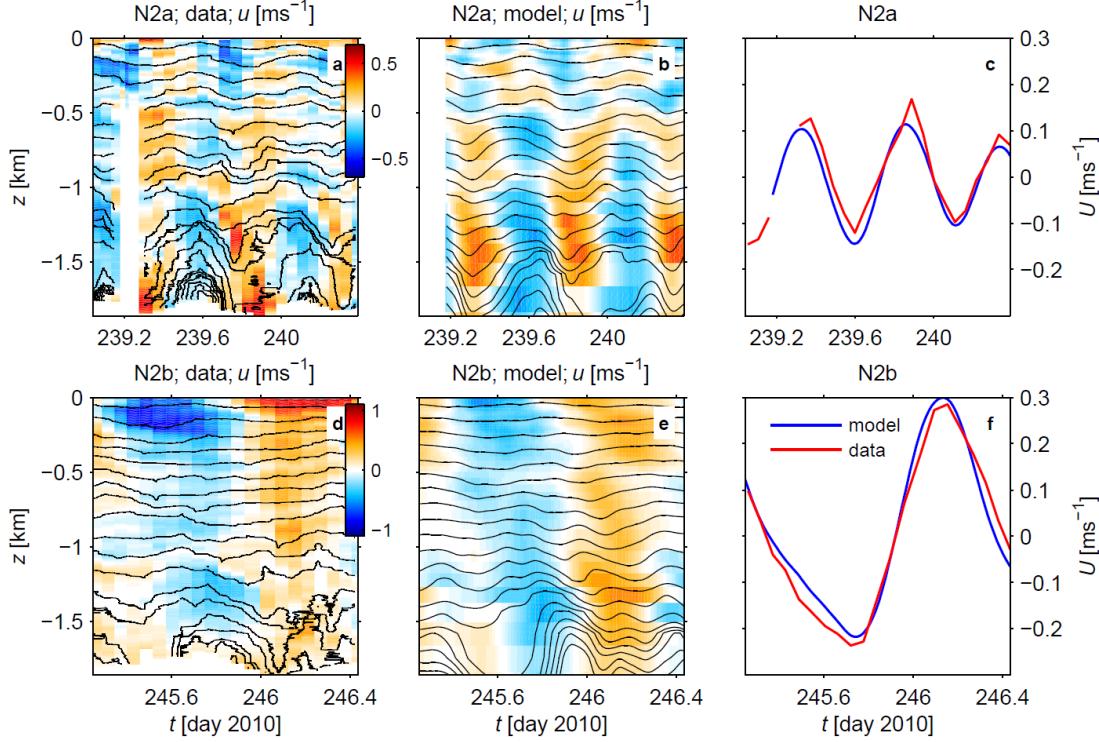


Figure 1. a) Fig. 3. Observed (a) and predicted (b) zonal velocities (colors) and density (contours), and (c) observed and predicted barotropic velocities for station N2a (Alford et al, 2011). when semidiurnal tides are dominant. (d)-(f) show the same but for station N2b when diurnal tides are dominant. The density is contoured every 100 m for an ocean at rest. The barotropic means are removed from the zonal velocities.

In the double ridge experiment, the semidiurnal and diurnal energy fluxes (vectors) and the barotropic to baroclinic energy conversion are dominated by mode 1 (Figure 2). The central Strait features two ridges that are equidistant for about 90 km over a north south distance of 150 km ($20\text{--}21.2^\circ\text{N}$). In this area, during semidiurnal tides, the first-mode conversion is positive on both the inner slopes of the west and east ridges. This is an indication that the wave fields radiated from both ridges are in phase with the barotropic forcing during semidiurnal tides. In contrast, the sign of the conversion at the inner slopes is opposite to that of the opposing ridge during diurnal tides, indicating that the wave fields are out of phase. These results are in agreement with the 2D model results. In the 3D model, the semidiurnal interference between the opposing wave fields causes standing wave phenomena characterized by the clockwise mode 1 flux gyre in the central basin (Figure 2a). The kinetic energy has a maximum in the center of the flux gyre, while the available potential energy is largest at the boundaries (not shown).

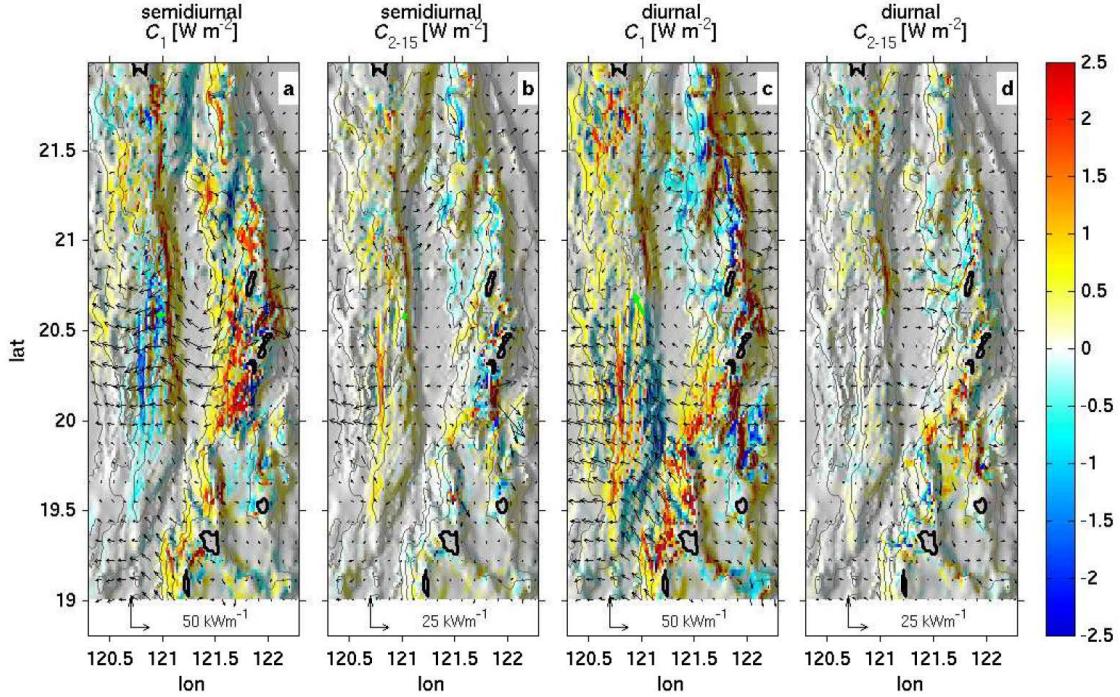


Figure 2. The semidiurnal time-mean and depth-integrated conversion and fluxes for (a) mode 1 and (b) the sum of modes 2-15. (c) and (d) show the same for diurnal tides.

The barotropic to baroclinic energy conversion is computed for the double and single ridge experiments. The difference between the area-integrated conversion in the double ridge and the sum of the single ridge cases, normalized by the sum of the single ridge cases is referred to as the amplification Ψ . The amplification is plotted as a function of latitude in Figure 3. The amplification is positive during semidiurnal tides (constructive interference) and negative during diurnal tides (destructive interference). It is largest in the center of the Strait, where the flux gyre resides. The amplification is mainly due to mode 1 (Figure 3b). The amplification of the higher modes is less coherent (Figure 3c). Curiously in the central Strait, the amplification in the 3D model is much larger than in the 2D numerical (triangles) and knife edge models (thick lines) (Klymak et al 2012). Ongoing research shows that the strong amplification in the 3D model compared to the 2D model can be attributed to 1) a better phasing between the three-dimensional first-mode waves and the barotropic Kelvin wave, 2) larger vertical barotropic velocities due to the redirection of the barotropic flow by the opposing ridge, and 3) a more equal wave generation at both ridges due to blocking of the barotropic flow at the east ridge.

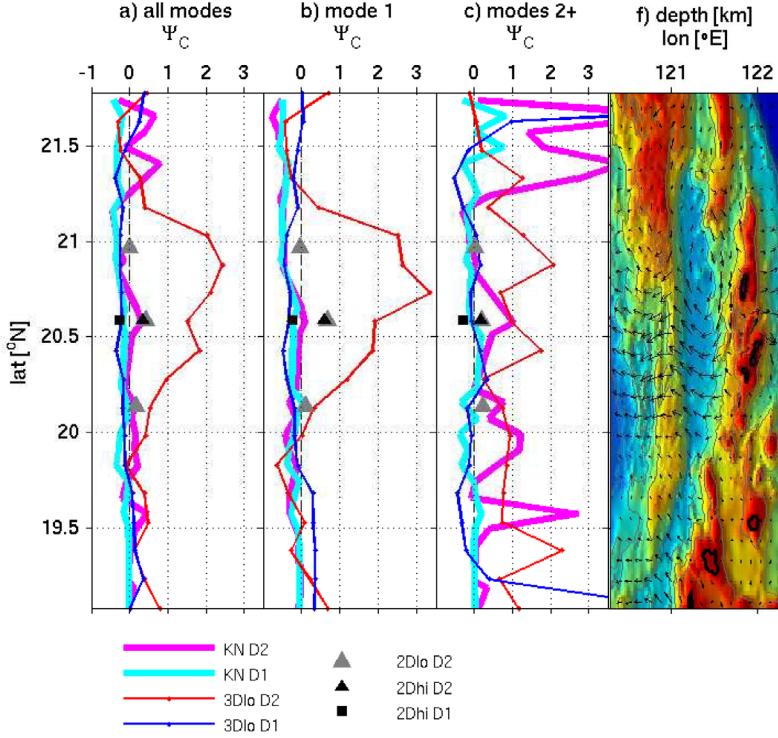


Figure 3. The zonally integrated amplification of the conversion for (a) all modes, (b) mode 1, and (c) modes 2 and higher as a function of latitude and tidal frequency for various models. KN is the 2D knife-edge model (Klymak et al 2012); lo(hi) is low (high) resolution. (f) The bathymetry in Luzon Strait and semidiurnal mode-one fluxes.

Dissipation Hotspots in the South China Sea

In addition to the low resolution 3D model runs two sets of high resolution model runs have been performed to investigate the dissipation hotspots and how these are affected by the 3D topography. One set is a four-day model run with mainly semidiurnal tides in August 2010 and the other a ten-day run in 2011, overlapping with the data collection efforts. The model grid features a high resolution in the center of the Strait of 250 m that is telescoped to several km at the model boundaries. The vertical grid comprises up to 154 layers, with a resolution that is high enough to capture overturns in breaking internal waves. The stratification only varies along the vertical axis. The 2011 results have been shared with the observationalists to aid them understanding their data.

The strongest dissipation on the west ridge occurs on top of the tallest ridges that feature steep supercritical slopes, whereas on the east ridge the strongest dissipation occurs in the deepest channels between the islands (Figure 4). On the east ridge the islands block the flow, which is forced through the deep channels, whereas on the west ridge the tallest ridges have the strongest currents. The dissipation is due to breaking lee waves that are very similar to 2D lee waves. The fraction of the barotropic to baroclinic energy conversion lost to local dissipation is 30%, i.e. 70% of the wave energy is radiated. This ratio is larger than the 19% at the Hawaiian ridge (Carter et al 2008). It shows that the double ridge system is a fairly good dissipator.

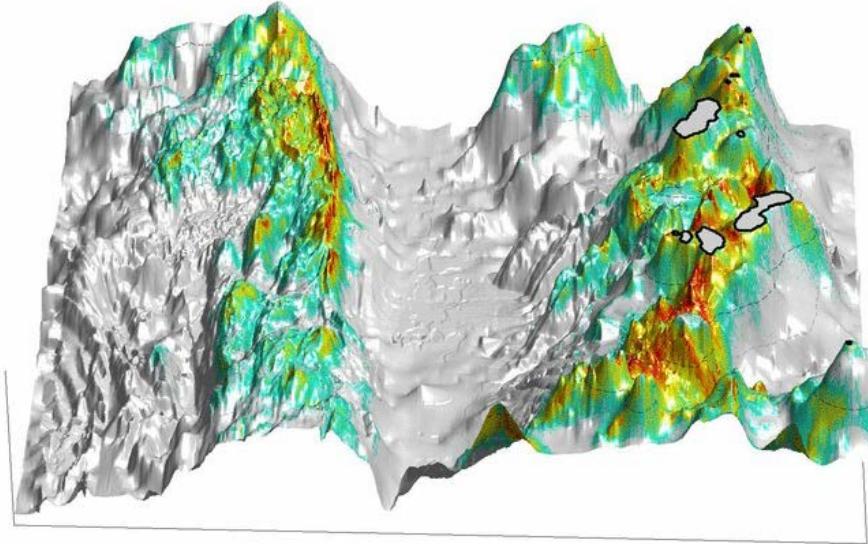


Figure 4. Three-dimensional topography of the central Strait, with superposed tidal-mean dissipation. Red is high and green is low dissipation. Islands are marked by the thick black line. The top is north and the bottom is south. The Pacific Ocean (South China Sea) is to the right (left).

IMPACT/APPLICATIONS

These simulations have provided important information on the 3-D flow and turbulence in the Luzon Strait system, information which is contributing to general understanding of internal waves on complex geometry, and aiding in the interpretation of observations in this specific region. Three papers have been published so far: Buijsman et al (2012), Klymak et al (2012a), and Pinkel et al (2012). A fourth is under review (Klymak et al 2012b). A manuscript is in preparation describing the 3D results. This work has been presented at the Warnemunde Turbulence Days 2011 and Ocean Sciences 2012.

RELATED PROJECTS

This work is a component of the Internal Waves in Straits Experiment. We are working closely with other IWSE researchers, particularly Jody Klymak, Rob Pinkel and Matthew Alford. The work is also related to an NSF/NOAA-funded climate process team on internal-wave driven mixing (PI Jen MacKinnon), with which Legg is collaborating.

REFERENCES

Alford, M. H., et al., 2011: Energy flux and dissipation in Luzon Strait: two tales of two ridges. *J. Phys. Oceanogr.*, doi:10.1175/JPO-D-11-073.1.

Carter, G. S., Merrifield, M. A., Becker, J. M., Katsumata, K., Gregg, M. C., Luther, D. S., Levine, M. D., Boyd, T. J., Firing, Y. L., 2008. Energetics of M2 Barotropic-to-Baroclinic Tidal Conversion at the Hawaiian Islands, *J. Phys. Oceanogr.*, 38, 2205-2223.

Buijsman, M.C., Legg, S., and Klymak, J., 2012. Double ridge internal tide interference and its effect on dissipation in Luzon Strait. *J. Phys. Oceanogr.*, 42, 1337–1356.

Klymak, J.M., Legg, S., Alford, M.H., Buijsman, M., Pinkel, R., and Nash, R., 2012a. The Direct Breaking of Internal Waves at Steep Topography. *Oceanography* 25(2):150–159, <http://dx.doi.org/10.5670/oceanog.2012.50>.

Klymak, J.M., M. Buijsman, S. Legg and R. Pinkel, 2012b: Parameterizing baroclinic internal tide scattering and breaking on supercritical topography: the one- and two-ridge cases. *J. Phys. Oceanogr.* Submitted.

Klymak, J. M. and S. Legg, 2010: A simple mixing scheme for models that resolve breaking internal waves. *Ocean Modell.*, 33, 224–234.

Legg S., and J. Klymak, 2008: Internal Hydraulic Jumps and Overturning Generated by Tidal Flow over a Tall Steep Ridge. *Journal of Physical Oceanography*, v38, 1949–1964.

Pinkel, R., Buijsman, M., and Klymak, J.M.. 2012. Breaking topographic lee waves in a tidal channel in Luzon Strait. *Oceanography* 25(2):160–165, <http://dx.doi.org/10.5670/oceanog.2012.51>.

PUBLICATIONS

Buijsman, M.C., Legg, S., and Klymak, J., 2012. Double ridge internal tide interference and its effect on dissipation in Luzon Strait. *J. Phys. Oceanogr.*, 42, 1337–1356. [published, refereed]

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